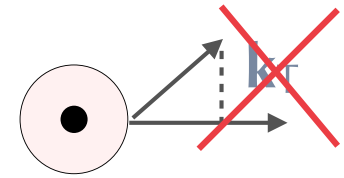
What do we know about transversity distributions of the nucleon?

Alexei Prokudin

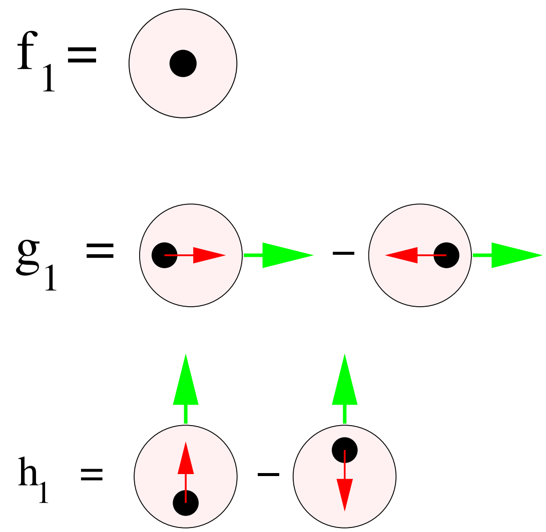
PennState
Berks

Leading-twist TMD map → PDF map



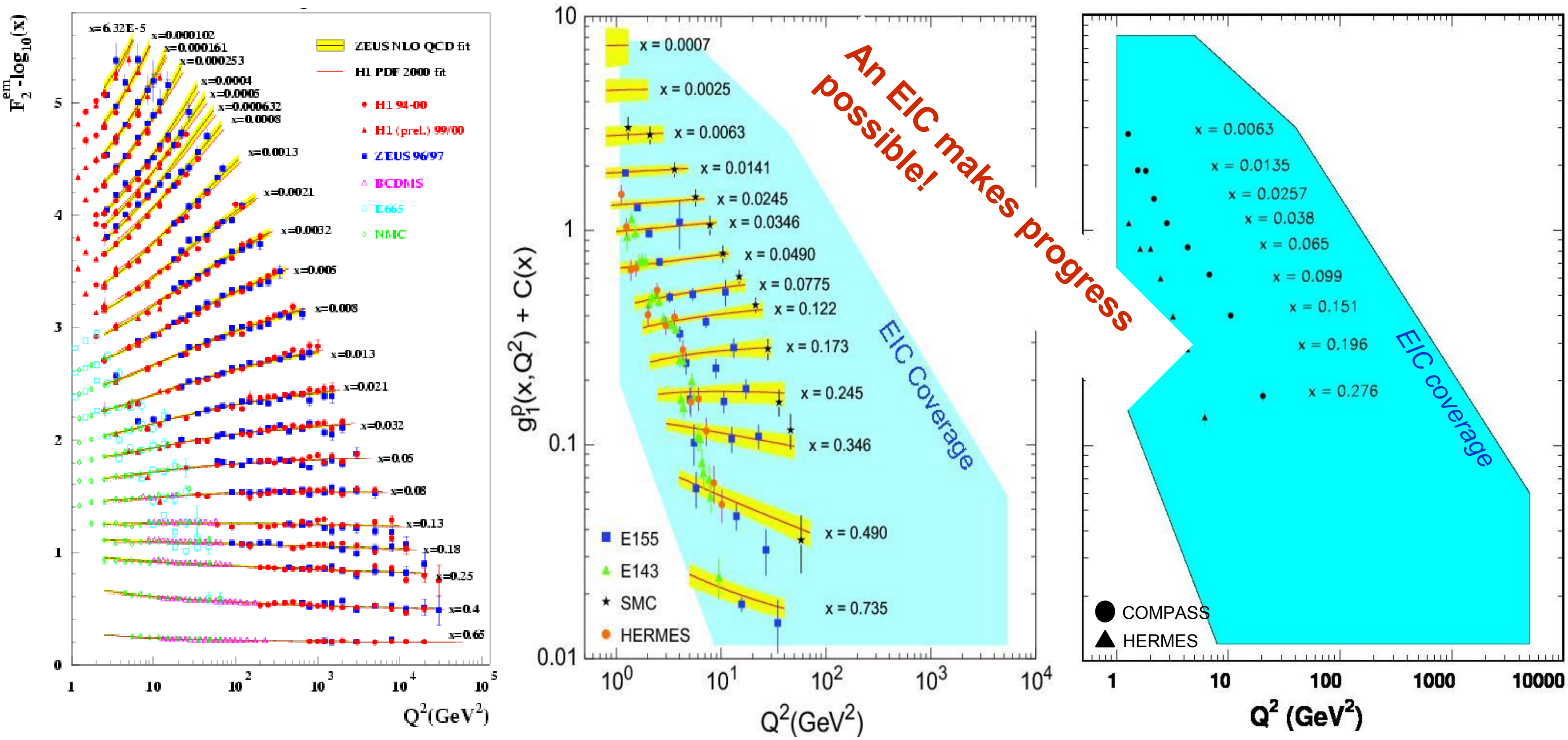
quark polarization

nucleon polarization	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



h_1 is the transversity distribution

Transversity is poorly known?



World data for F_2^p
f_1 from fits of
thousands data

World data for g_1^p
g_1 from fits of
hundreds data

World data for h_1
from fits of **tens** data

Tensor Charge

See talk of Rajan Gupta

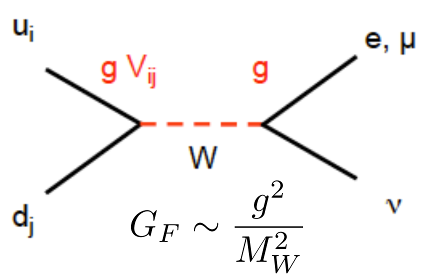
- 1st Mellin moment of transversity $\Rightarrow$ tensor "charge"

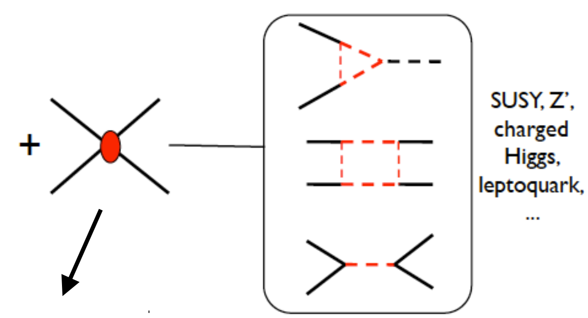
$$\delta q \equiv g_T^q = \int_0^1 dx \; \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2) \right]$$

> tensor charge not directly accessible in $\mathbf{L}_{SM}$
> low-energy footprint of new physics at higher scales ?

Example: neutron β−decay $\quad n \to p\, e^- \, \overline{\nu}_e$

SM





BSM

$$\varepsilon_T \, g_T \approx M_W^2 \,/\, M_{BSM}^2$$

Current precision of 0.1% $\Rightarrow$ [3-5] TeV bound for BSM scale

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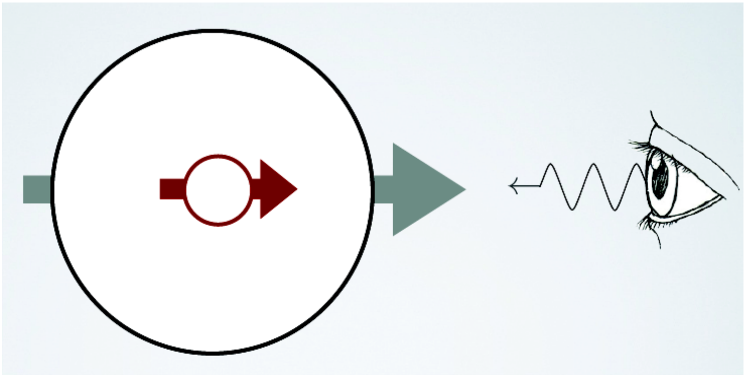
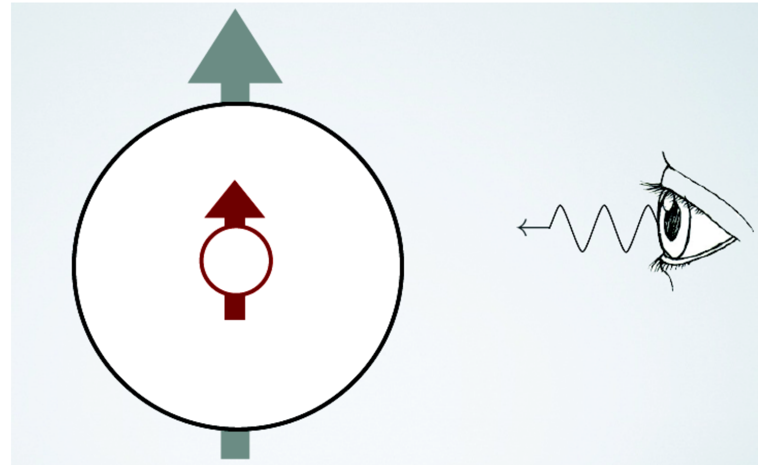
slide courtesy of M. Radici

What did we know about transversity before the EIC whitepaper ?

Helicity distribution

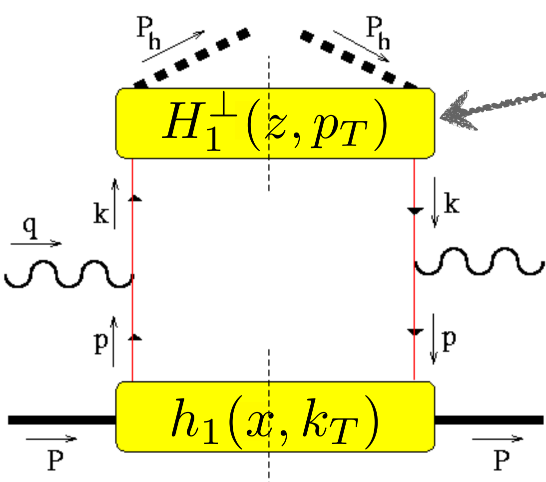


Transversity distribution



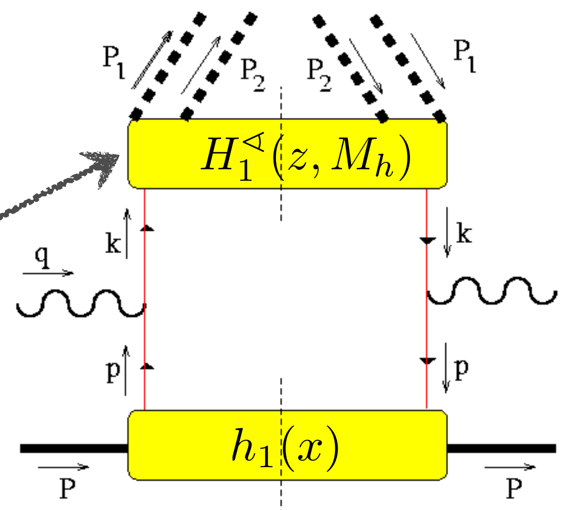
Boost and rotation do not commute → helicity and transversity are different!

Transversity is a chiral odd quantity → needs another chiral odd quantity to be measured in Semi Inclusive Deep Inelastic Scattering (SIDIS)



Collins function

Di hadron fragmentation function



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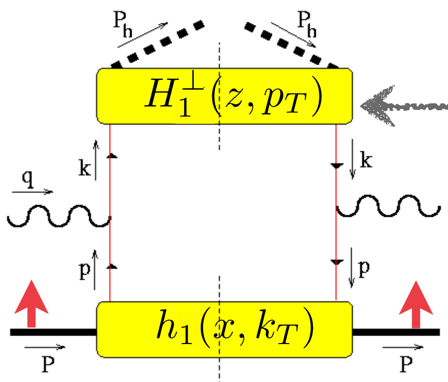
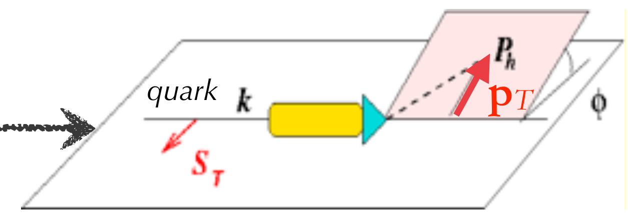
First extractions of transversity: the Collins effect

one-hadron SIDIS

Collins (1992)



Collins function



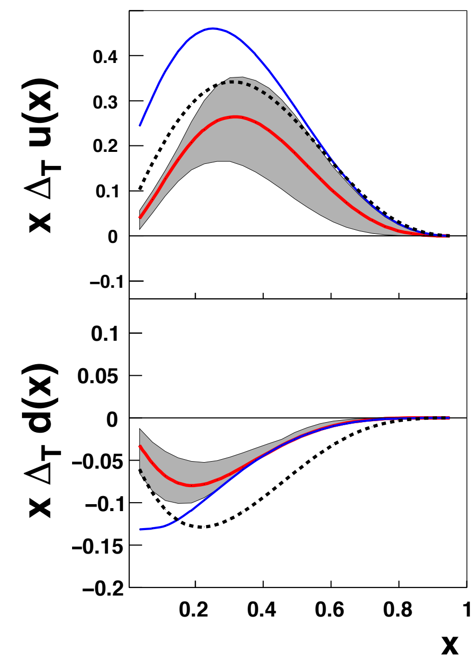
$$\sin(\phi_h + \phi_S)$$

correlation $\mathbf{S}_T$ and $\mathbf{p}_T$
$\rightarrow$ azimuthal asymmetry

TMD factorization

$$A_{\mathrm{SIDIS}}^{\sin(\phi_h+\phi_S)}(x, z, P_T^2) \sim \frac{\sum_q e_q^2 \; h_1^q(x, \boldsymbol{k}_\perp^2) \otimes H_{1,q}^\perp(z, \boldsymbol{p}_\perp^2)}{\sum_q e_q^2 \; f_1^q(x, \boldsymbol{k}_\perp^2) \otimes D_{1,q}(z, \boldsymbol{p}_\perp^2)}$$

Efremov et al (2005), Vogelsang, Yuan (2005), Anselmino et al (2005,2009), Collins et al (2006)…



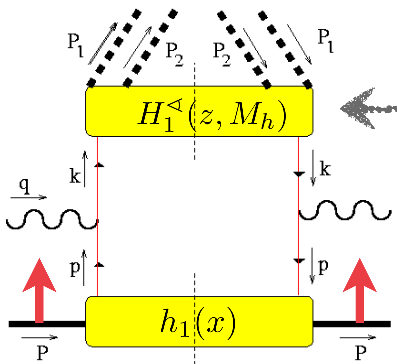
SIDIS data from hermes and COMPASS

e^+e^- data from Belle II

Anselmino et al., Nucl.Phys.Proc.Suppl. 191 (2009) 98-107

di-hadron fragmentation (DiFF)

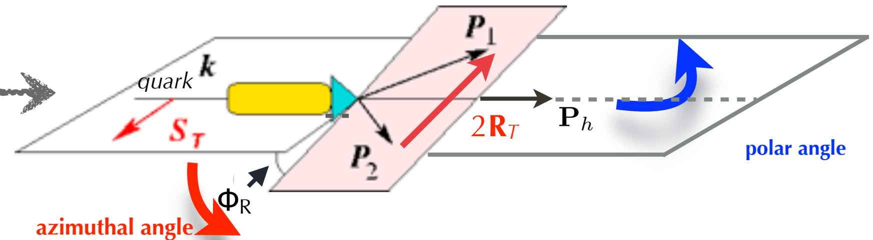
one-hadron SIDIS



Di hadron fragmentation function

$$\sin(\phi_R + \phi_S)$$

Collins, Heppelman, Ladinsky (1994)



correlation between quark pol. $\mathbf{S}_T$ and $2\mathbf{R}_T$
→ azimuthal asymmetry

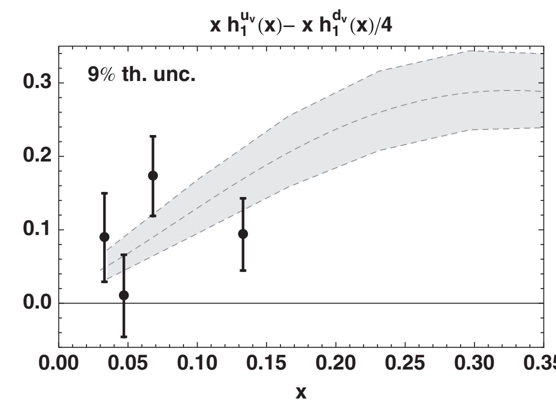
Collinear factorization

Radici, Jakob, Bianconi, (2002)

chiral-odd DiFF

$$A_{\text{SIDIS}}^{\sin(\phi_R+\phi_S)}(x, z, M_h^2) \sim -\frac{\sum_q e_q^2\ h_1^q(x)\ \frac{|\boldsymbol{R}_T|}{M_h}\ H_{1,q}^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2\ f_1^q(x)\ D_{1,q}(z, M_h^2)}$$

$z = z_1 + z_2$
price to pay: dependence on ($\pi\pi$) invariant mass M_h

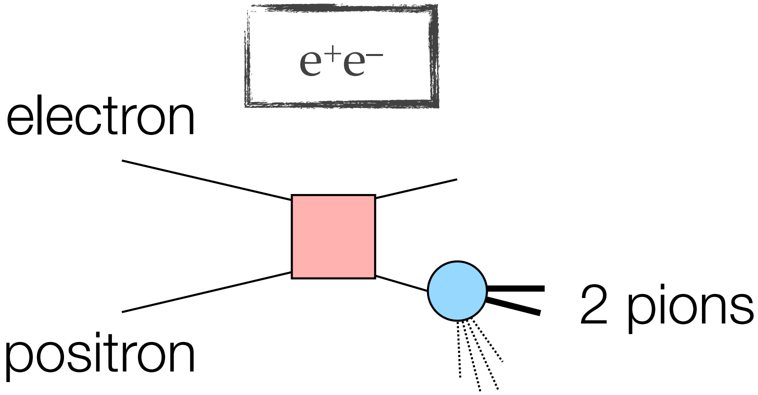


Bacchetta, Courtoy, Radici (2011)

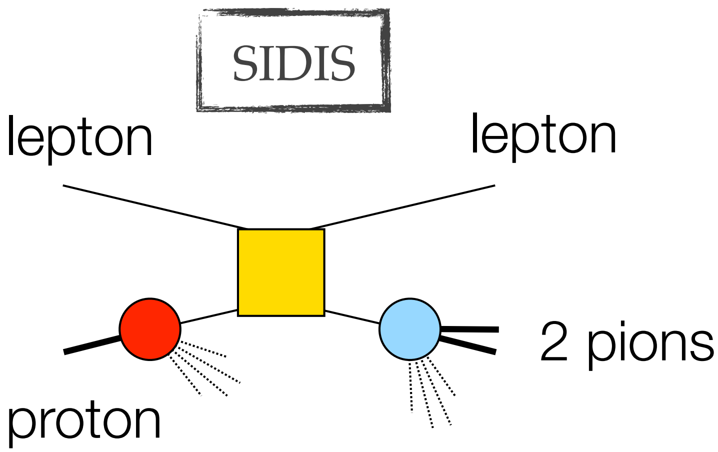
slide courtesy of M. Radici

What about factorization for other processes ?

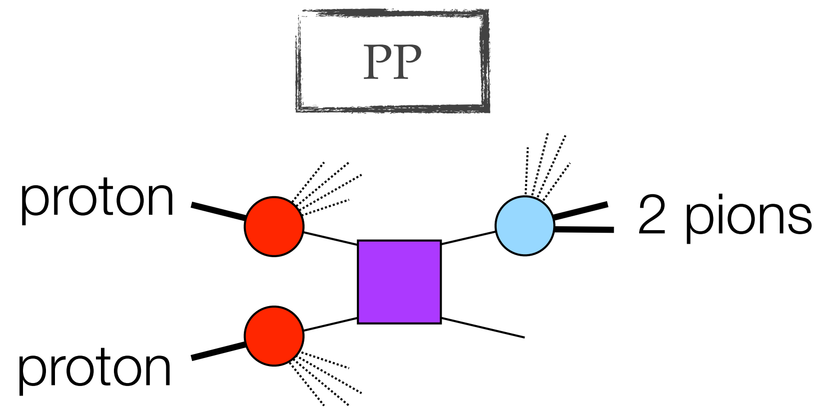
Collinear factorization for **dihadron** production



Artru & Collins, Z.Phys. ***C69*** *(96) 277*
*Boer, Jakob, Radici, P.R.D**67** (03) 094003*

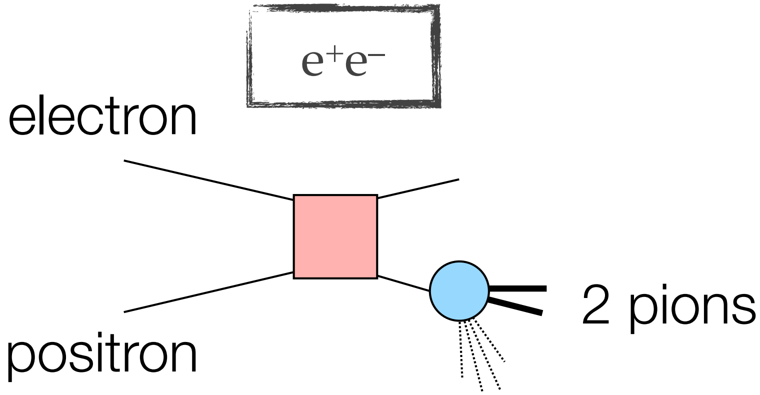


*Jaffe, Jin, Tang, P.R.L.**80** (98) 1166*
*Radici, Jakob, Bianconi, P.R.D**65** (02) 074031*
*Bacchetta & Radici, P.R. D**67** (03) 094002*



*Bacchetta & Radici, P.R. D**70** (04) 094032*

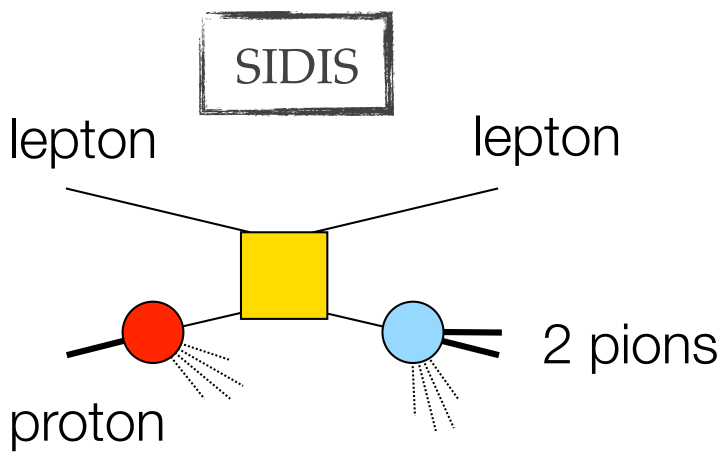
Collinear factorization for **dihadron** production



Artru & Collins, Z.Phys. ***C69*** *(96) 277*
*Boer, Jakob, Radici, P.R.D**67*** *(03) 094003*

*DeFlorian & Vanni, P.L.**B578*** *(04) 139*
*Ceccopieri, Radici, Bacchetta, P.L.**B650*** *(07) 81*
Zhou and Metz, P.R.L. ***106*** *(11) 172001*
(M_h—evolution of DiFFs)

Standard DGLAP evolution equations



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*Radici, Jakob, Bianconi, P.R.D**65*** *(02) 074031*
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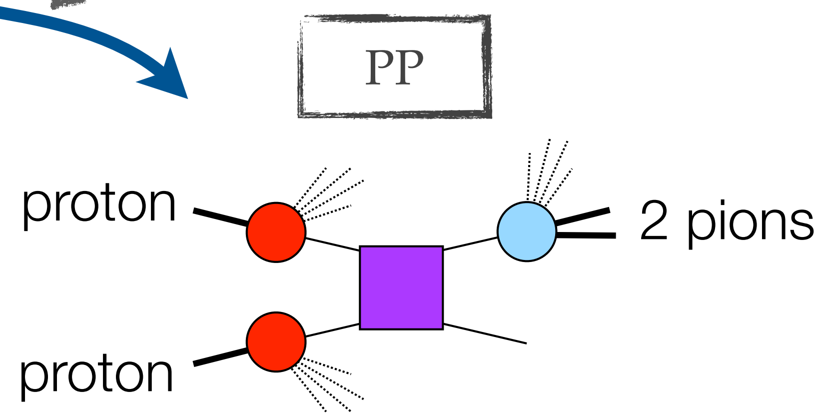
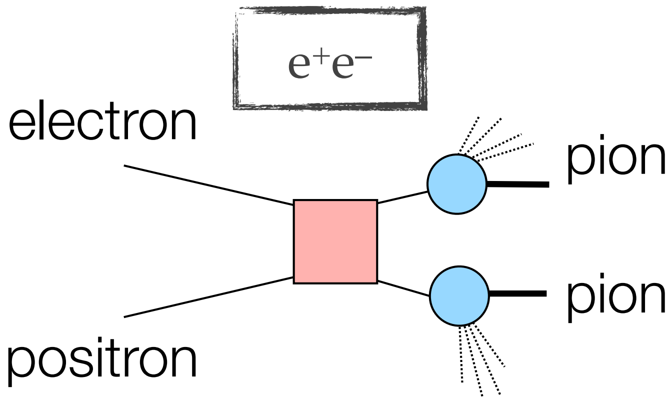
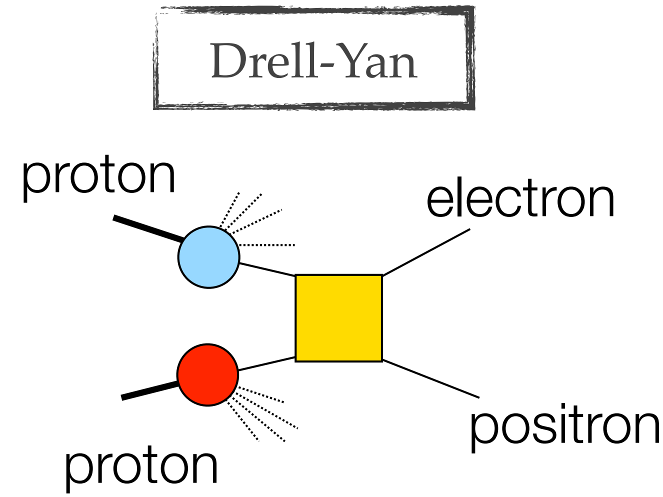


*Bacchetta & Radici, P.R. D**70*** *(04) 094032*

TMD factorization



Collins, Soper, Sterman (1985)
Collins (2011)



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

- TMD factorization is valid generically for processes with two measured scales Q1 << Q2.
- Traditionally called "resummation" by CSS for cross sections.
- Later put in the form of evolution equations for TMD functions by Collins 11.
- Complicated color flow makes it difficult to prove factorization with > 2 hadrons involved.

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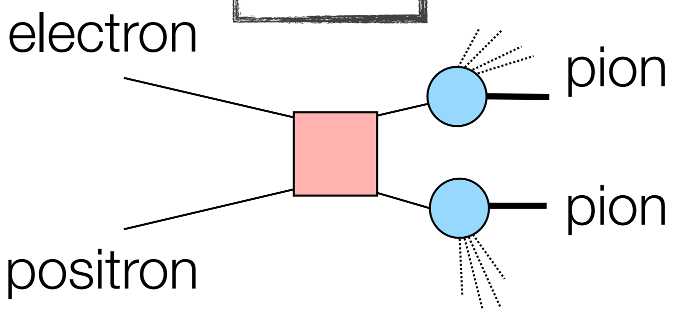
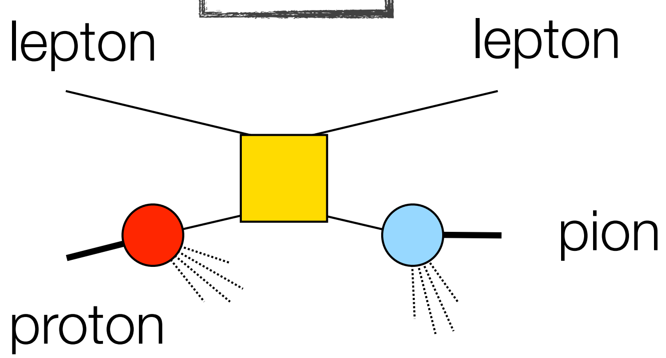
TMD factorization

e^+e^-



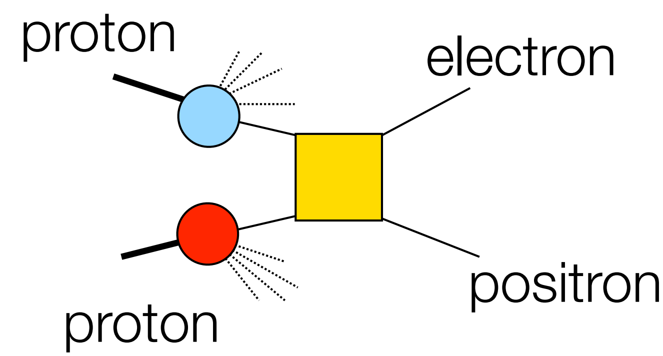
Collins, Soper, Sterman (1985)
Collins (2011)

SIDIS



Ji, Ma, Yuan (2005)
Collins (2011)

Drell-Yan



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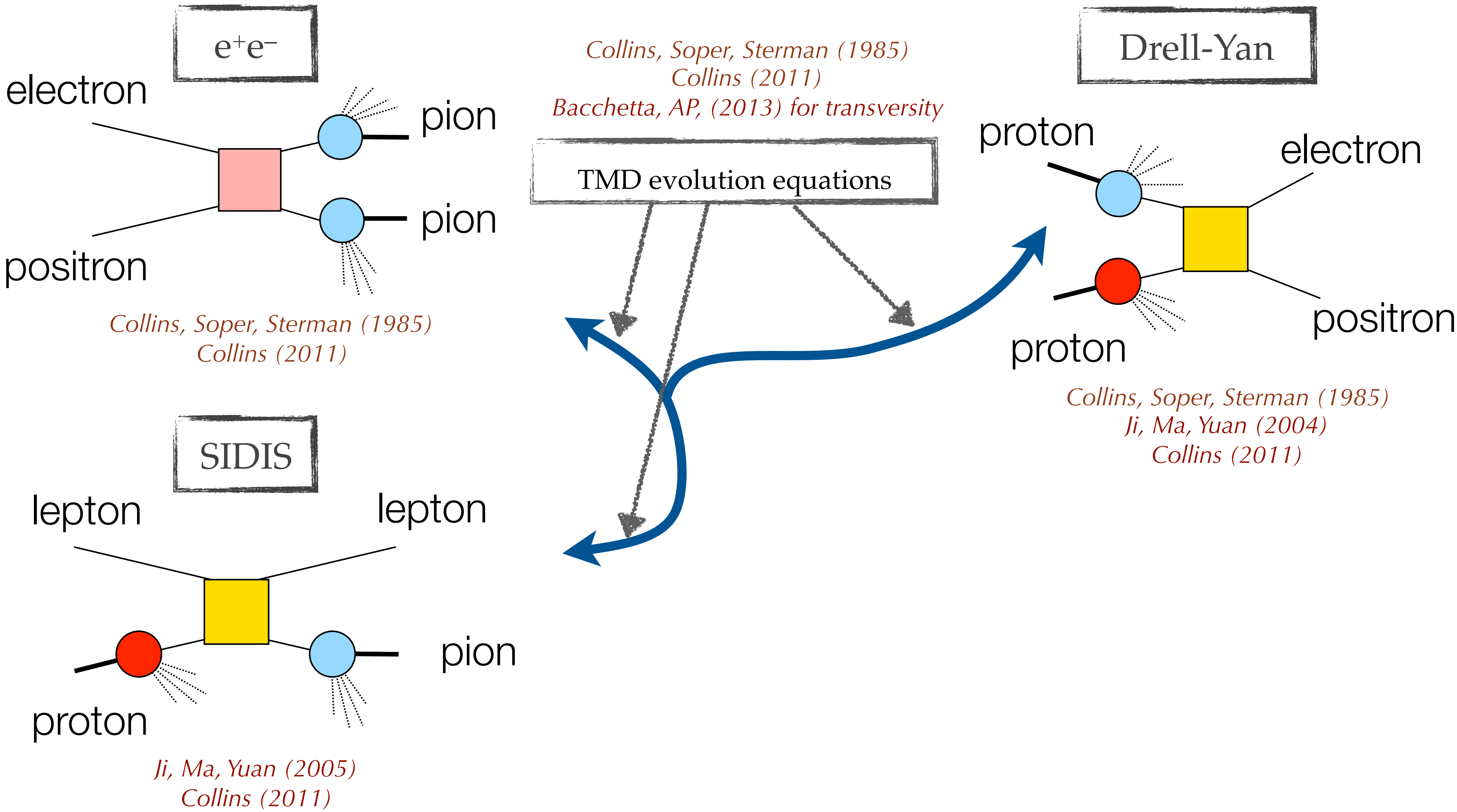
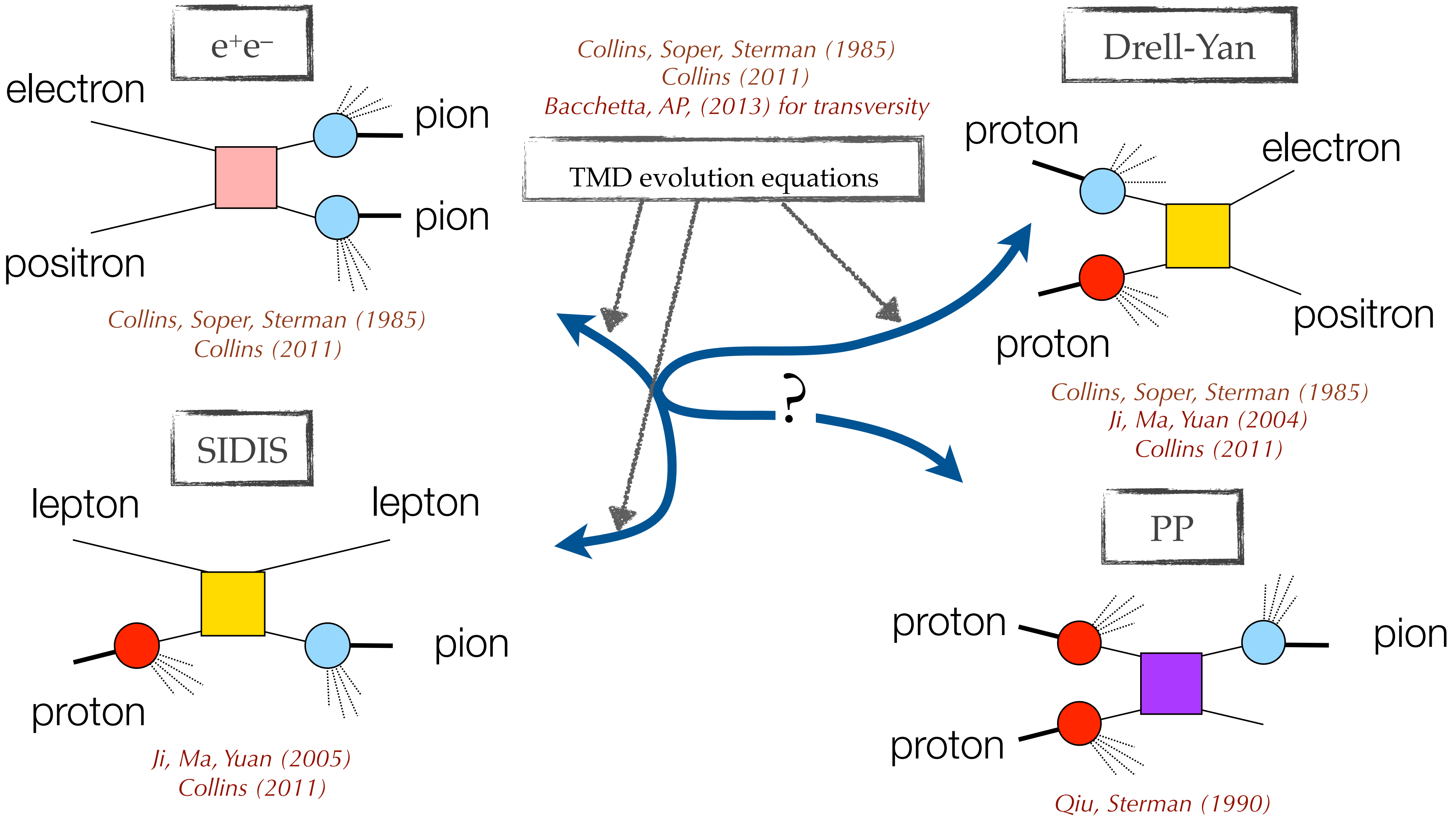
Ji, Ma, Yuan (2004)
Collins (2011)

TMD factorization

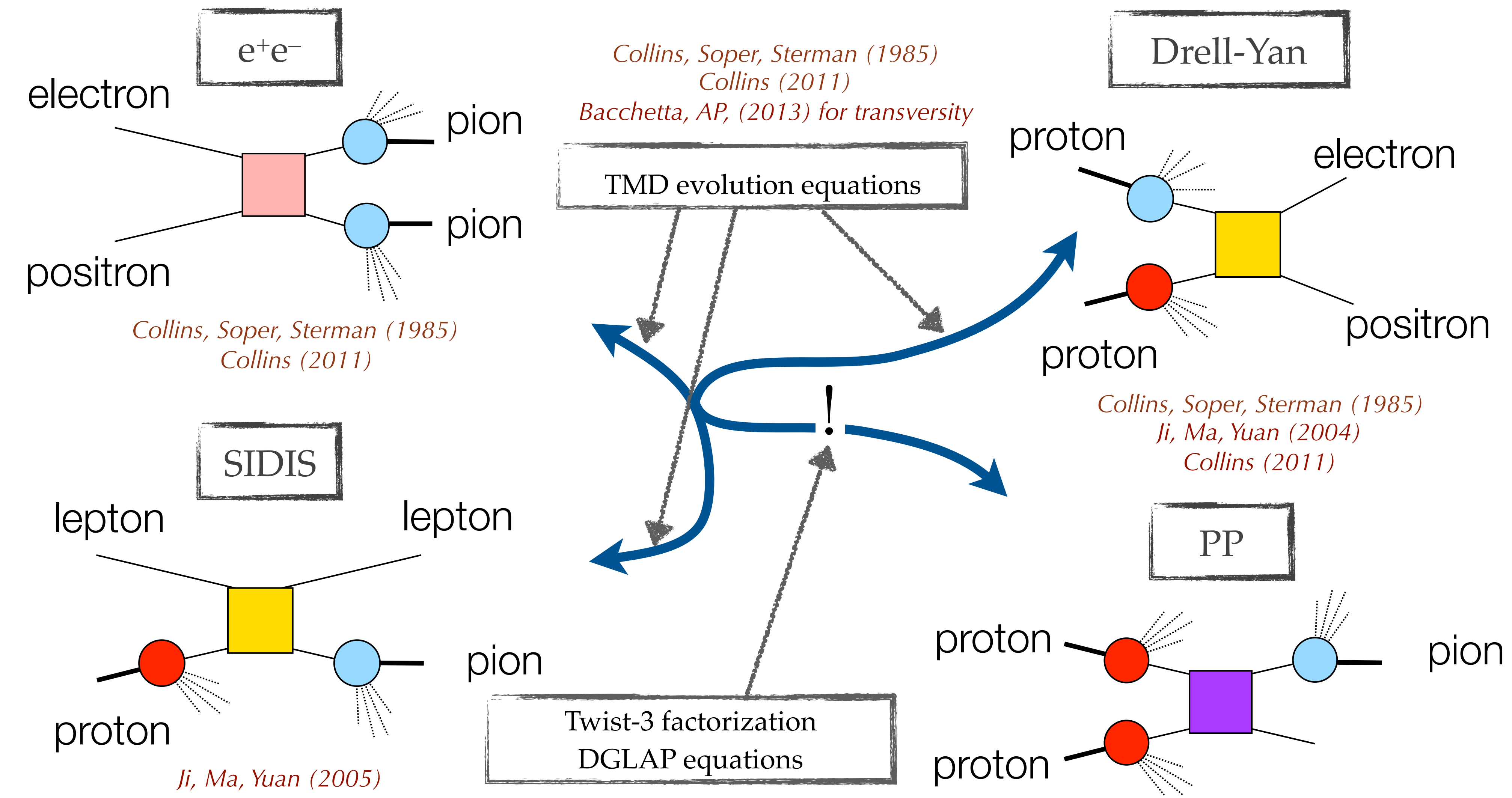


TMD factorization



Only one scale is measured in PP
TMD factorization is not applicable?

TMD factorization



- Twist-3 functions are related to TMD via OPE
- TMD and twist-3 factorizations are related in high QT region
- Global analysis of TMDs and twist-3 is possible: All four processes can be used.
- Data are from HERMES, COMPASS, JLab, BaBar, Belle, RHIC, LHC, Fermilab

Global fit is needed.
Work in progress

See talks by Daniel Pitonyak, Zhongbo Kang, Nobuo Sato

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What have we learnt about transversity after the EIC whitepaper ?

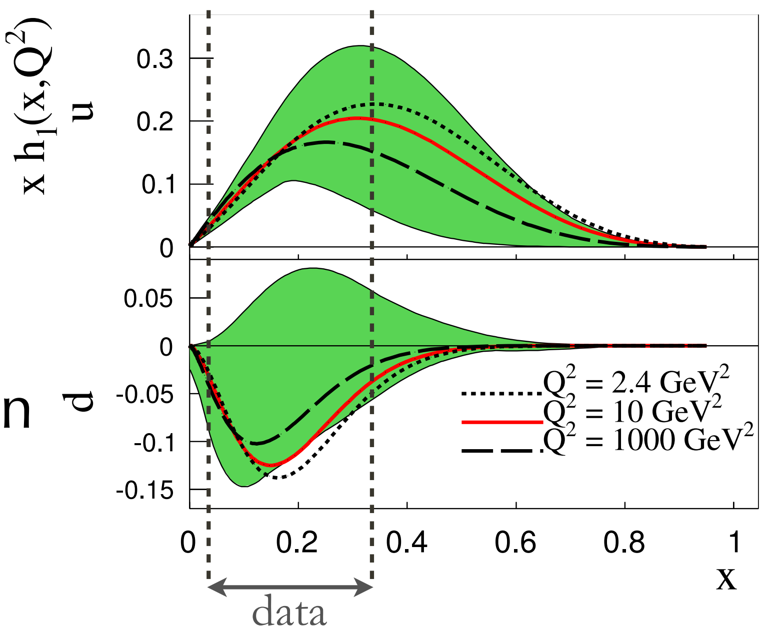
TMD fits: transversity and Collins FF

The first fit using TMD evolution

*Kang et al., P.R. D**93** (16) 014009*

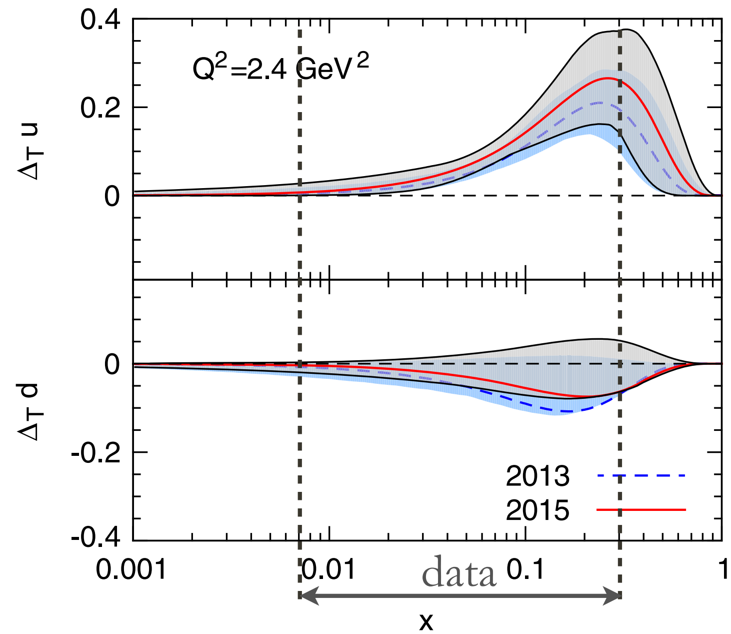
up

down



Fits without TMD evolution

*Anselmino et al., P.R. D**93** (15) 034025*



New data:

SIDIS data from hermes and COMPASS and Jefferson Lab

e^+e^- data from BABAR and Belle II

History of upgrading fits:

*Anselmino et al., P.R. D**87** (13) 094019*

*Anselmino et al., P.R. D**92** (15) 114023*

*Anselmino et al., P.R. D**93** (15) 034025*

TMD fits: transversity and Collins FF

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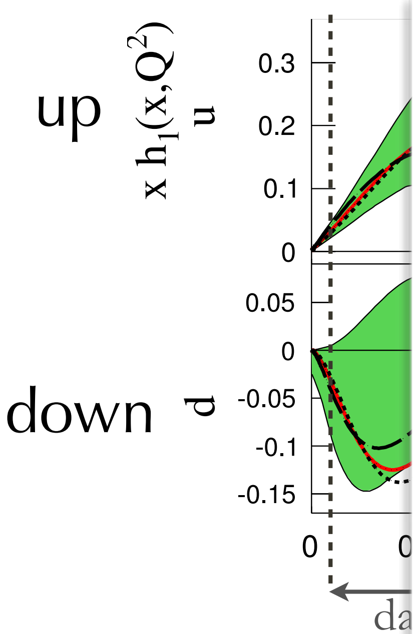

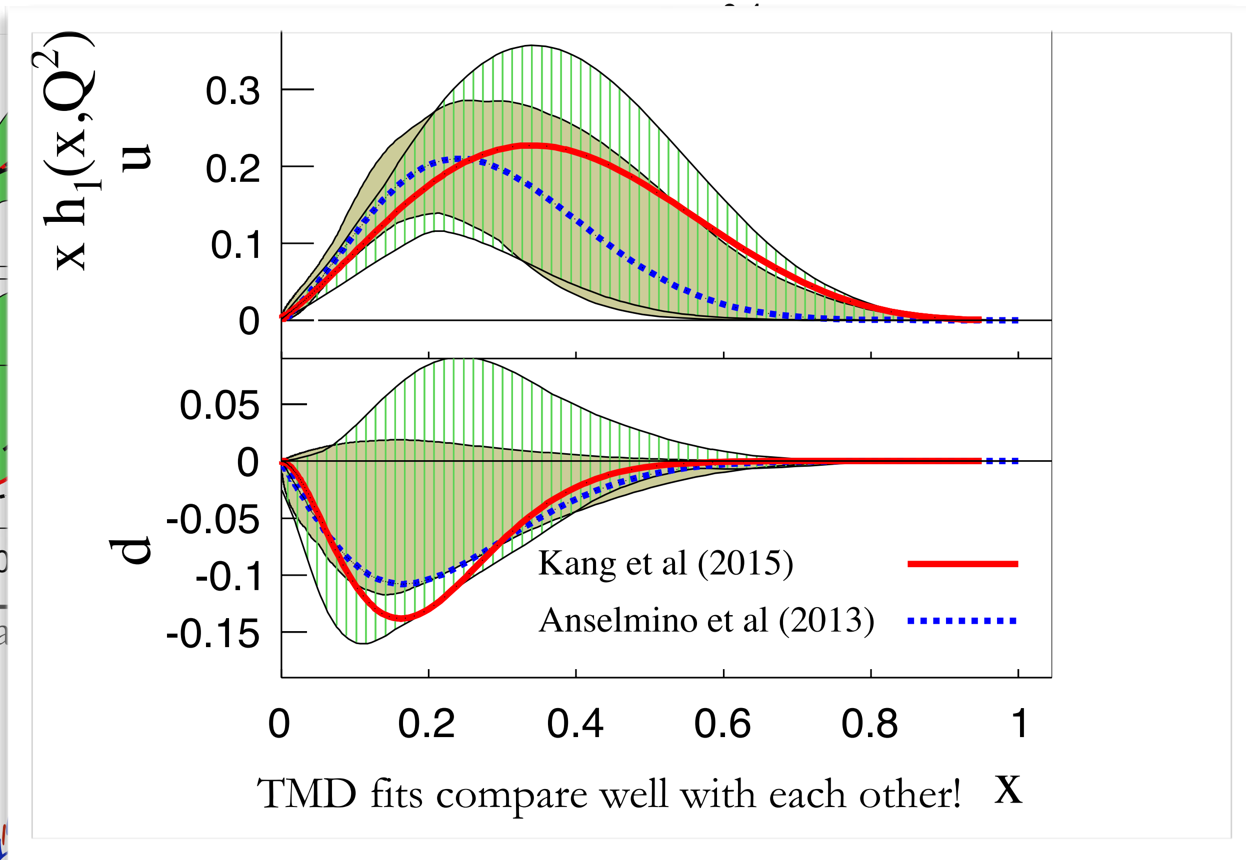

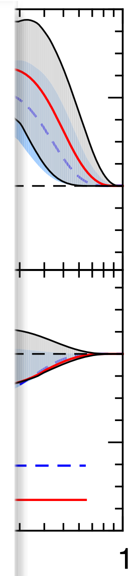

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*Anselmino et al., P.R. D**93** (15) 034025*

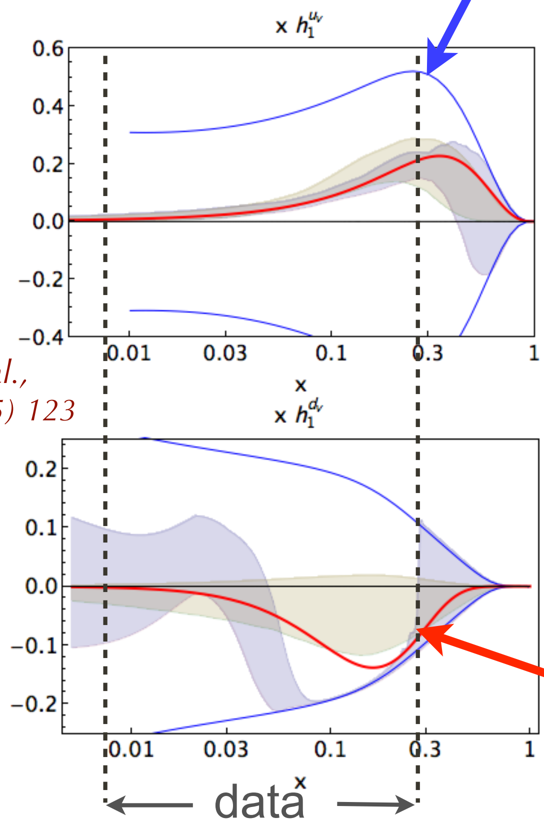
The Pavia fit: transversity and DiFF

Soffer bound $2|h_1^q(x,Q^2)| \le 2\,\mathrm{SB}_q(x) = |f_1^q(x) + g_1^q(x)|$

up

down

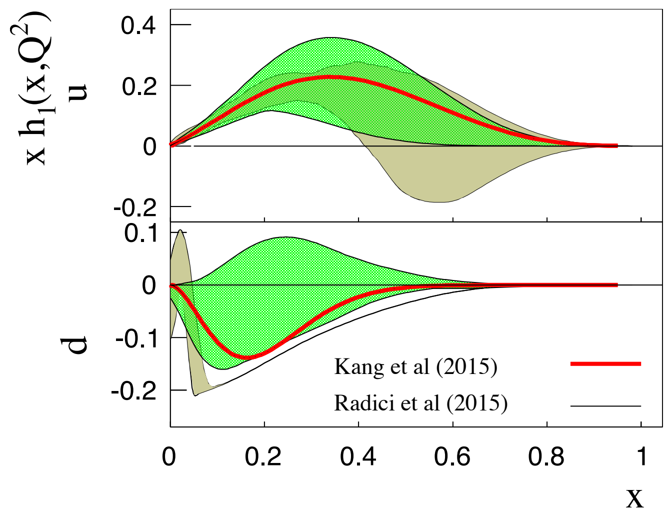
*Radici et al., JHEP **1505** (15) 123*



Anselmino et al., (2013)

Kang et al., (2015)

Kang et al. 2016 <-> Pavia 2015



Q^2=2.4 GeV^2

linear scale

New data:

SIDIS data from hermes and COMPASS

e^+e^- data from Belle II

History of upgrading fits:

*Bacchetta, Courtoy, Radici, P.R.L. **107** (11) 012001*

*Bacchetta, Courtoy, Radici, JHEP **1303** (13) 119*

*Radici et al., JHEP **1505** (15) 123*

slide courtesy of M. Radici

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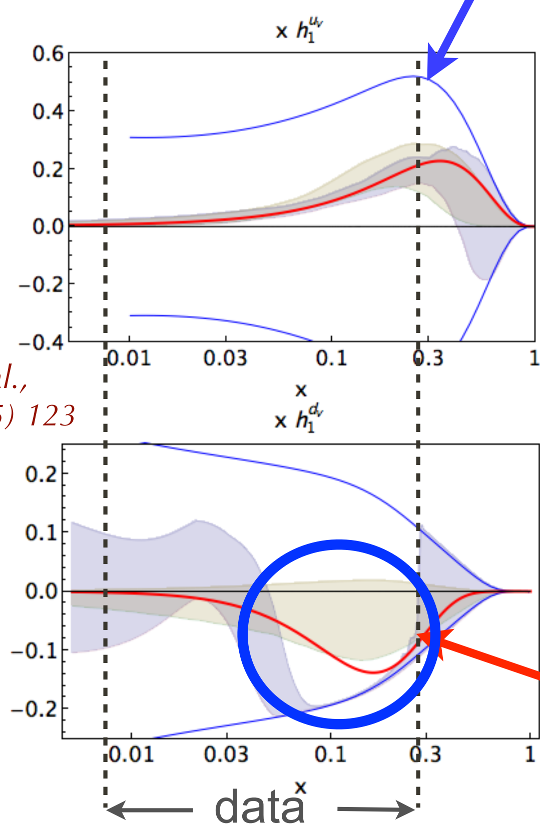
The Pavia fit: transversity and DiFF

Soffer bound $2|h_1^q(x,Q^2)| \leq 2\,\mathrm{SB}_q(x) = |f_1^q(x) + g_1^q(x)|$

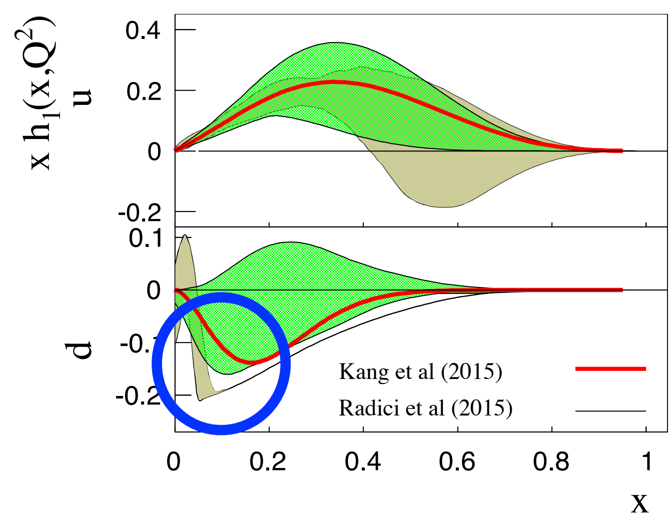
up

down



*Radici et al., JHEP **1505** (15) 123*

Kang et al. 2016 <-> Pavia 2015



Q^2=2.4 GeV^2

linear scale

Anselmino et al., (2013)

Kang et al., (2015)

unusual saturation of Soffer bound for down

New data:

SIDIS data from hermes and COMPASS

e^+e^- data from Belle II

History of upgrading fits:

*Bacchetta, Courtoy, Radici, P.R.L. **107** (11) 012001*

*Bacchetta, Courtoy, Radici, JHEP **1303** (13) 119*

*Radici et al., JHEP **1505** (15) 123*

slide courtesy of M. Radici

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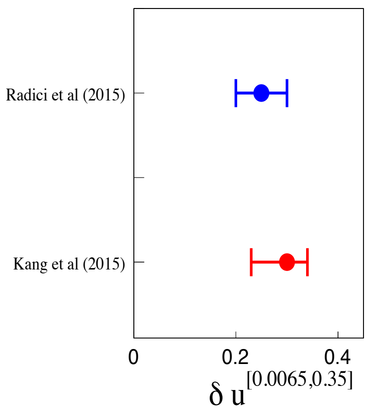
Tensor charge

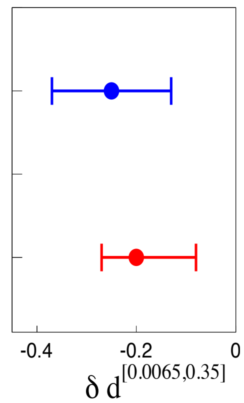
Q^2 = 10 GeV^2

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$



Radici et al. 2015

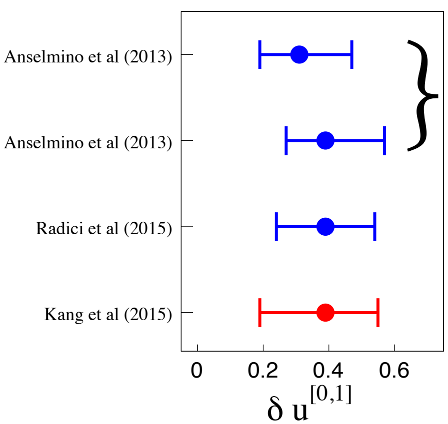
Kang et al. 2016



truncated to data range
$x \in [0.0065, 0.35]$

extrapolation to [0,1]

expect larger uncertainties



Anselmino et al. 2013

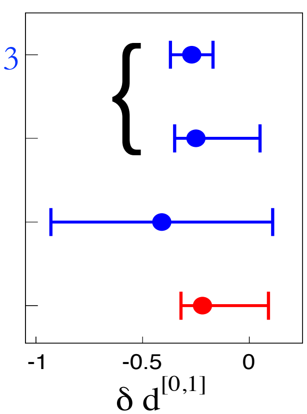
Q^2 = 0.8

Radici et al. 2015

Q^2 = 1

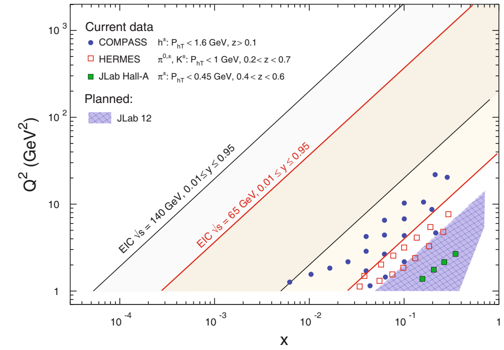
Kang et al. 2016

Q^2 = 10



Data from
- Electron Ion Collider
- Jefferson Lab
- RHIC

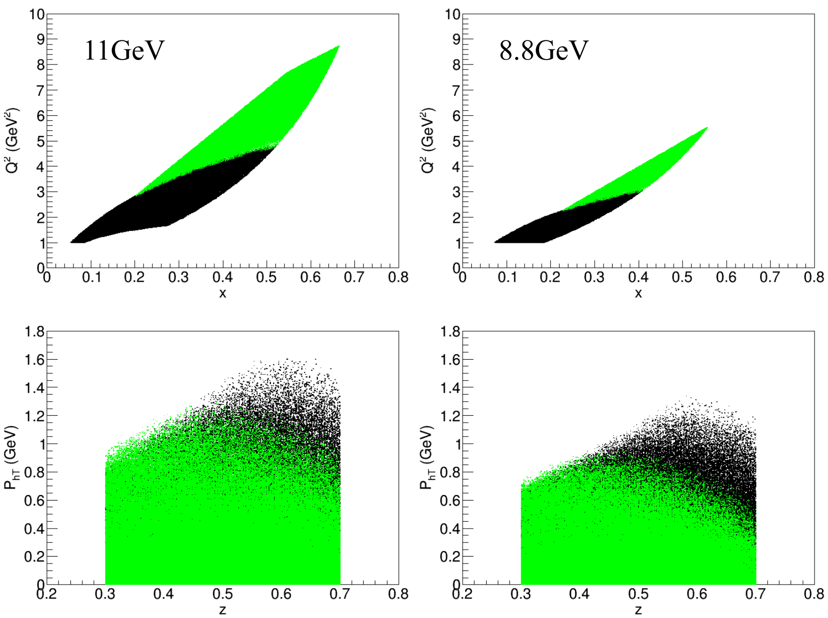
are going to reduce uncertainties

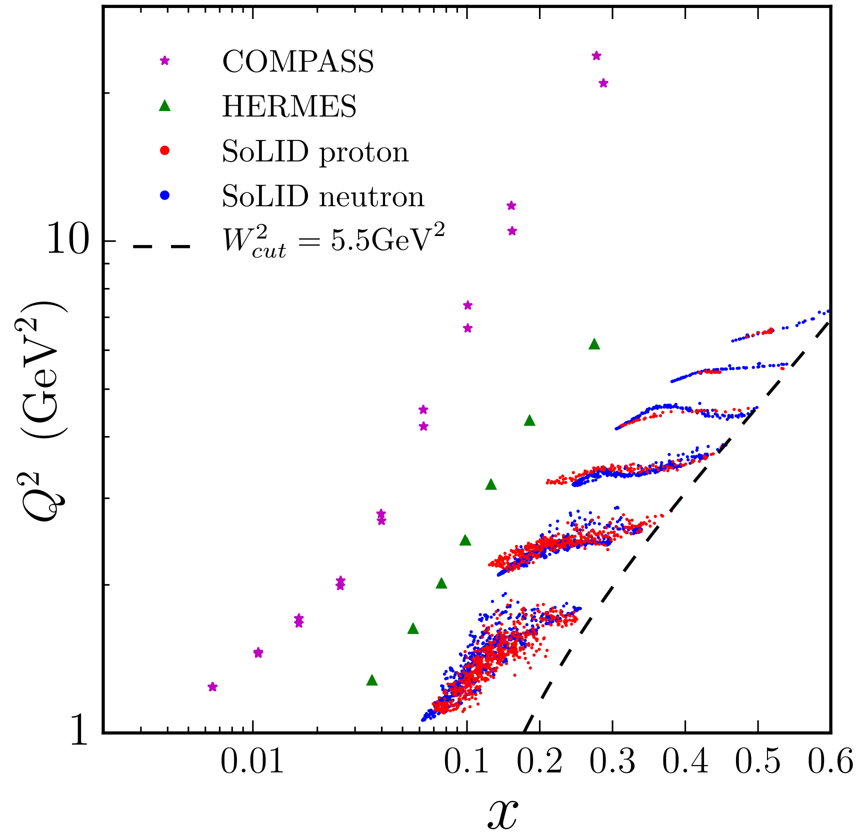


What will we learn about transversity at an EIC?

What do we expect from JLab 12?

- Electron beam: 11GeV and 8.8 GeV
- Targets: neutron (^3He) and proton (NH_3)
- Luminosity: ~ 10^{36} n cm^{-2} s^{-1}, 10^{35} p cm^{-2} s^{-1}
- Polar angle: 8° ~ 24°
- Azimuthal angle: full 2π coverage
- In beam polarization: ~60% (^3He), ~70% (NH_3)
- 4D bins with high precision

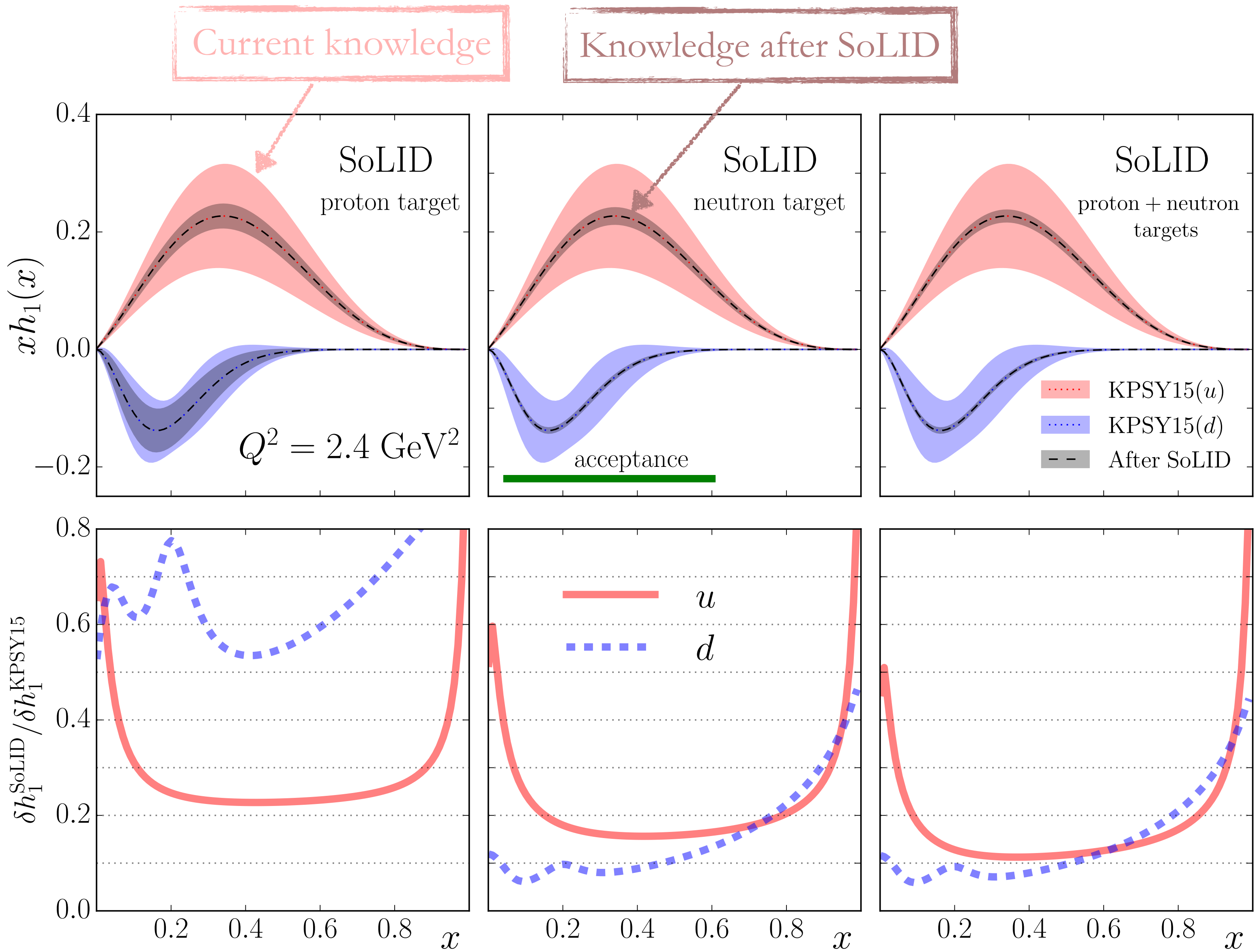




$0.3 < z < 0.7$
$W' > 1.6$ GeV
$Q^2 > 1.0$ GeV^2

Ye et al arXiv:1609.02449 (2016)

What do we expect from JLab 12?

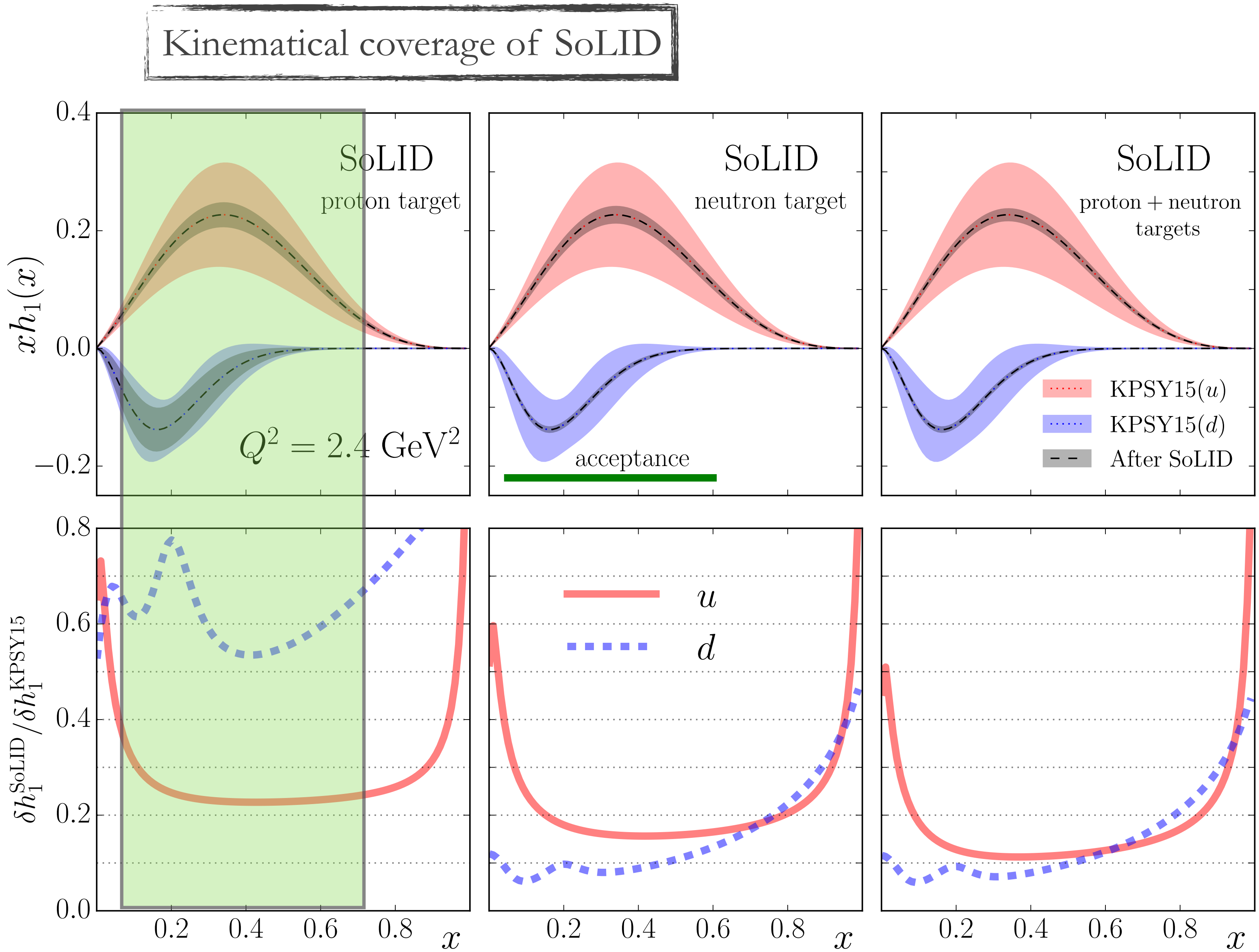


Bayesian statistics is used to estimate the improvement from new data

Current knowledge corresponds to a fit with TMD evolution *Kang et al., P.R. D**93** (16) 014009*

Ye et al arXiv:1609.02449 (2016)

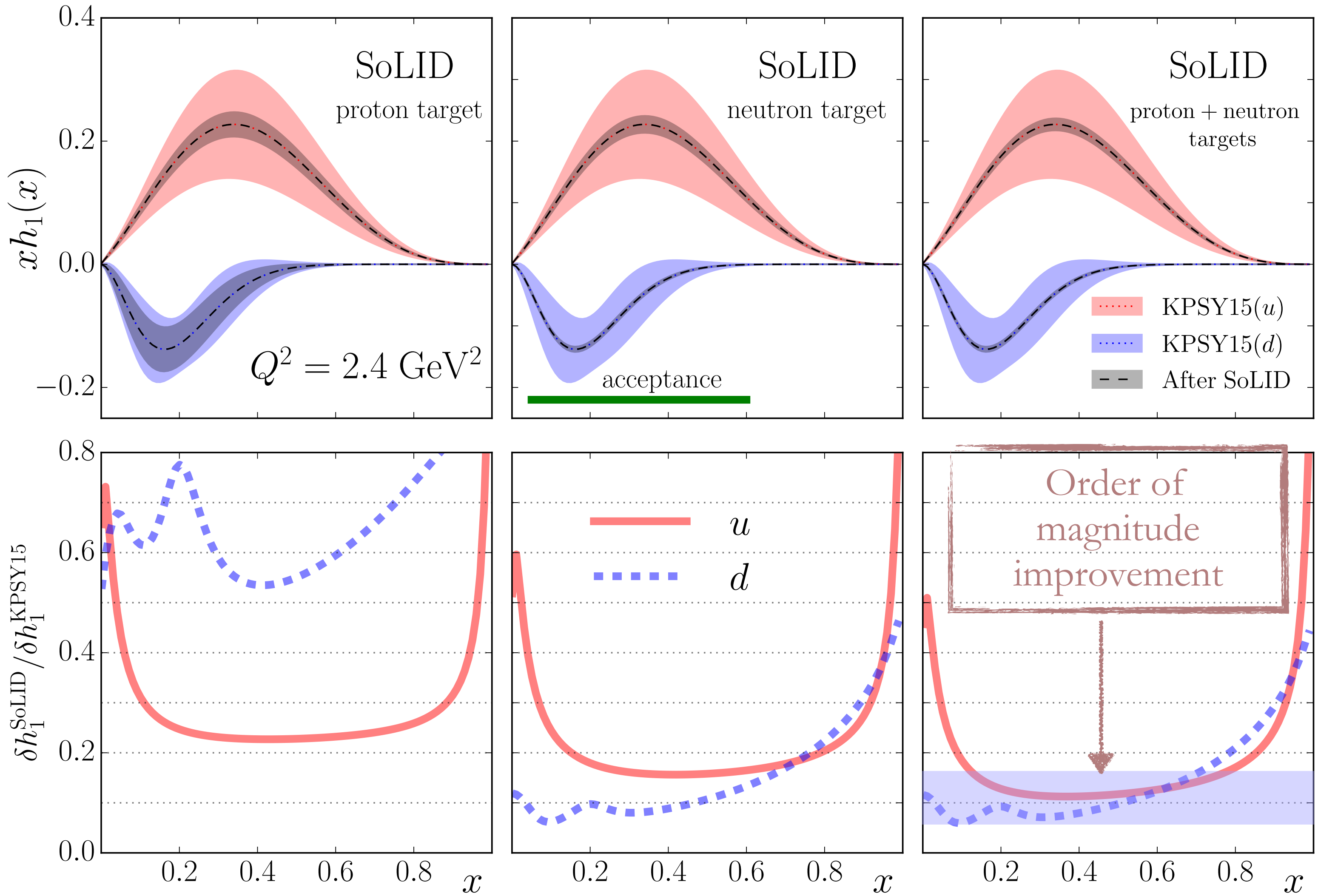
What do we expect from JLab 12?



The errors grow outside of the future data region as expected

Ye et al arXiv:1609.02449 (2016)

What do we expect from JLab 12?



Only combination of proton and neutron target measurements will ensure similar improvement for both u and d quark transversities

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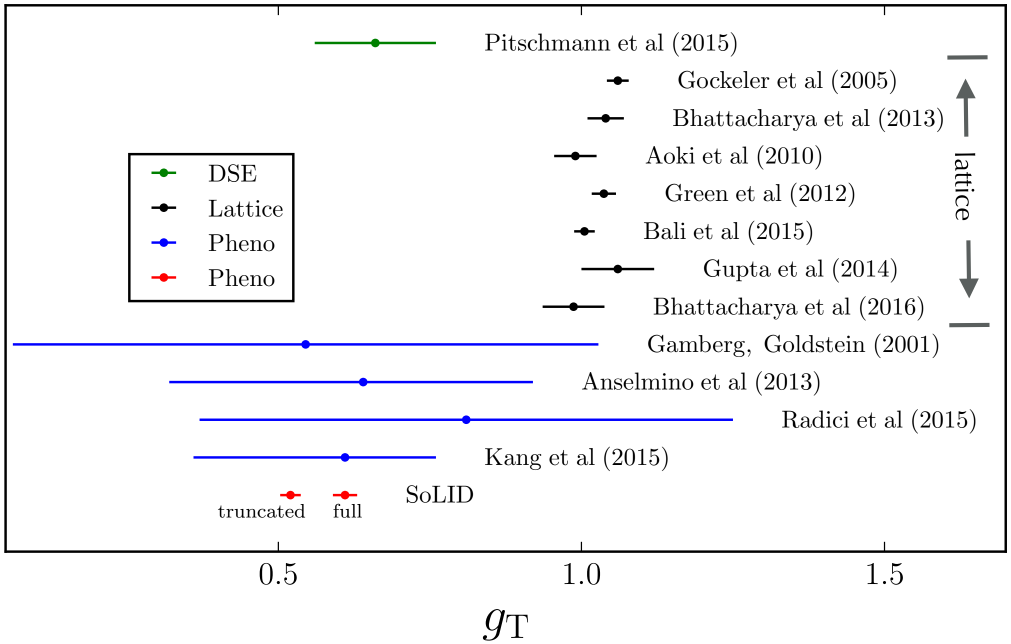
Ye et al arXiv:1609.02449 (2016)

What do we expect from JLab 12?

$$g_T = \delta u - \delta d$$ isovector tensor charge



- Order of magnitude improvement is expected
- **Truncated** result is more reliable as no extrapolation is used
- Comparable with lattice QCD precision

"full" is contribution from $0 < x < 1$ region
"truncated" is contribution from $0.05 < x < 0.6$

Ye et al arXiv:1609.02449 (2016)

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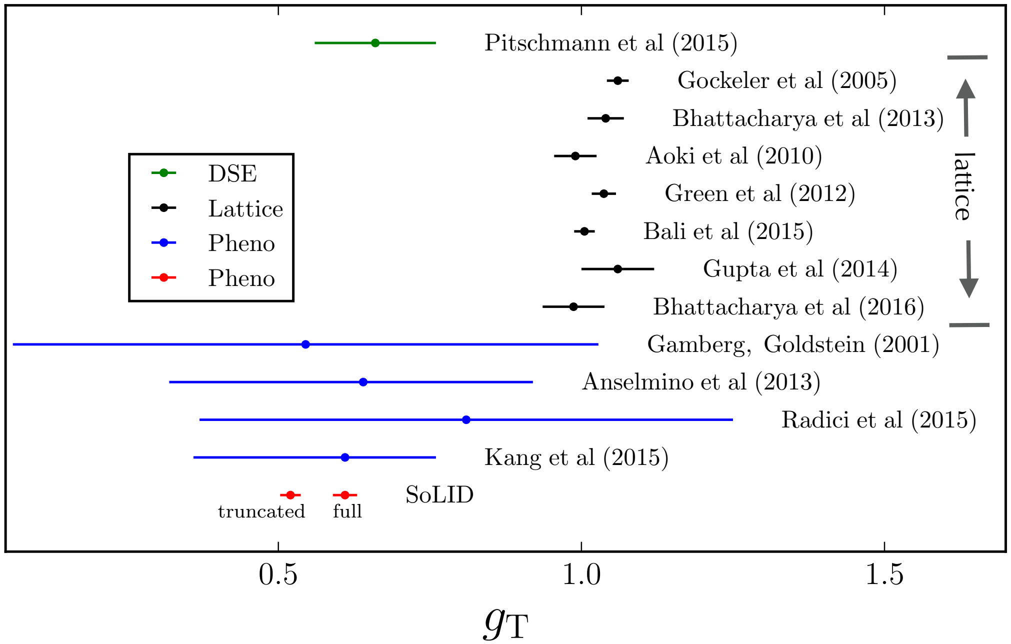

- Order of magnitude improvement is expected
- **Truncated** result is more reliable as no extrapolation is used
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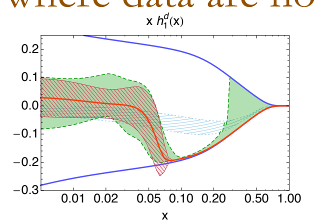
"full" is contribution from 0 < x < 1 region
"truncated" is contribution from 0.05 < x < 0.6

- Sea quark transversity is neglected
- Extrapolation can be unreliable in the region where data are not present



Radici et al (2015)

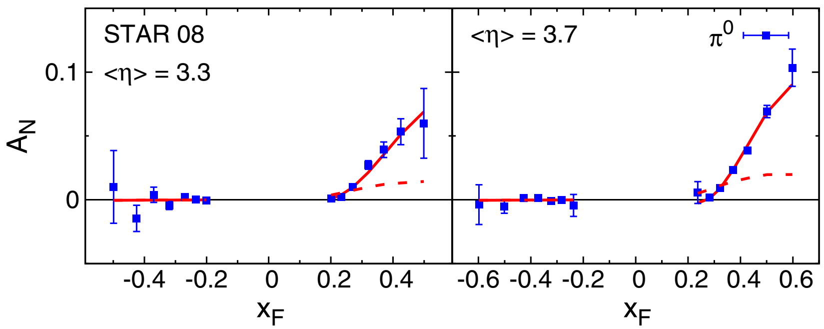
- Contribution from low-x region can be substantial: ~20% of tensor charge
  Ye et al arXiv:1609.02449 (2016)

Ye et al arXiv:1609.02449 (2016)

See talk by Daniel Pitonyak

RHIC: the process $p + p^{\uparrow} \to \pi + X$

Twist-3 factorization, fragmentation contributions



Kanazawa, Koike, Metz, Pitonyak (2014)

$$\frac{E_h d\sigma^{Frag}(S_P)}{d^3\vec{P}_h} = -\frac{4\alpha_s^2 M_h}{S}\,\epsilon^{P'PP_hS_P}\sum_i\sum_{a,b,c}\int_0^1\frac{dz}{z^3}\int_0^1 dx'\int_0^1 dx\;\delta(\hat{s}+\hat{t}+\hat{u})$$
$$\times\frac{1}{\hat{s}\,(-x'\hat{t}-x\hat{u})}\,h_1^a(x)\,f_1^b(x')\left\{\left[H_1^{\perp(1),\pi/c}(z)-z\frac{dH_1^{\perp(1),\pi/c}(z)}{dz}\right]S_{H_1^\perp}^i+\frac{1}{z}H^{\pi/c}(z)\,S_H^i\right.$$
$$\left.+\frac{2}{z}\int_z^\infty\frac{dz_1}{z_1^2}\frac{1}{\left(\frac{1}{z}-\frac{1}{z_1}\right)^2}\hat{H}_{FU}^{\pi/c,\Im}(z,z_1)\,S_{\hat{H}_{FU}}^i\right\},$$

Integration over **x** for transversity, conservation of momenta in $ab\to cd$: $x_{min} = -(U/z)/(T/z+S)$

$$\int_{x_{min}}^1\frac{dx}{x}$$

RHIC data is sensitive to high-x behavior of transversity
quark-gluon channel is dominant contribution for large x_F

More complicated structure of cross-section, additional functions to study

Improving errors in large-x region?
Analysis in progress.

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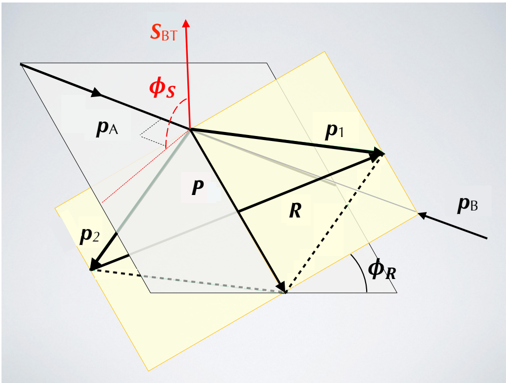


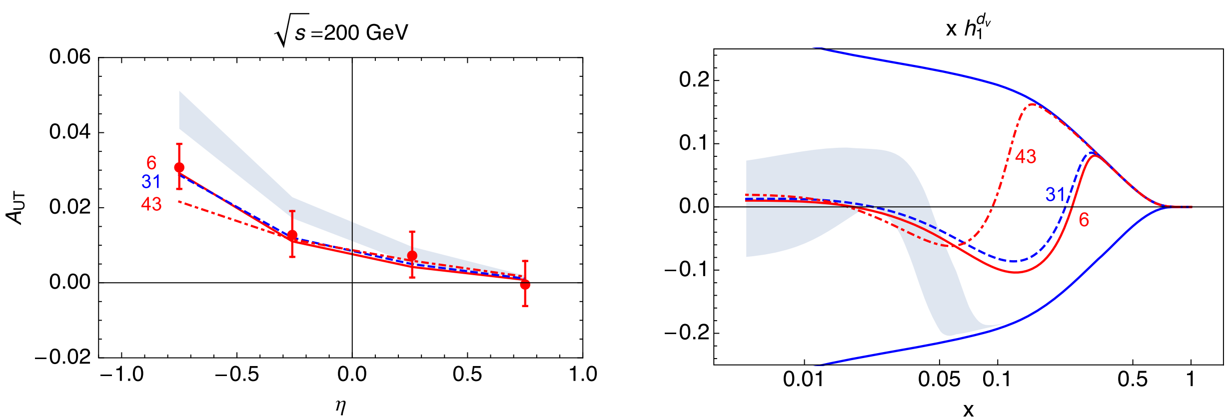
Bacchetta & Radici,
*P.R. D**70** (04) 094032*

Assuming universality of functions for this process

$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$

$$A_{UT}(\eta, |\boldsymbol{P}_T|, M_h) = \frac{|\boldsymbol{S}_{BT}| 2 |\boldsymbol{P}_T|}{d\sigma^0} \frac{|\boldsymbol{R}_T|}{M_h} \sum_{a,b,c,d} \int \frac{dx_a dx_b}{16\pi \bar{z}} \times f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow \to c^\uparrow d}}{d\hat{t}} H_1^{\sphericalangle c}(\bar{z}, M_h).$$

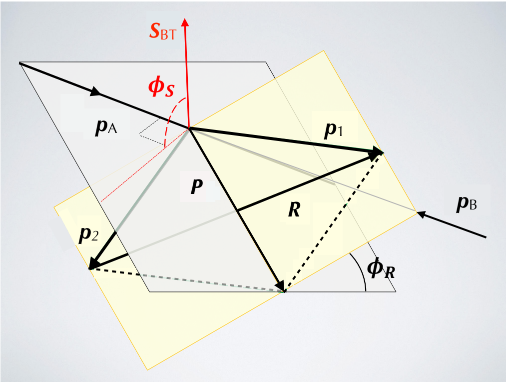
STAR data vs replicas in Pavia fit



some replicas outside the 68% band from SIDIS fit
show compatibility with p-p data in forward kinematics

*Radici et al, P.R. D**94** (16) 034032*

RHIC: the process $p + p^{\uparrow} \to (\pi\ \pi) + X$



Bacchetta & Radici,
*P.R. D**70** (04) 094032*

Assuming factorization and universality for this process

$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$

$$A_{UT}(\eta,|\boldsymbol{P}_T|,M_h) = \frac{|\boldsymbol{S}_{BT}|2|\boldsymbol{P}_T|}{d\sigma^0}\frac{|\boldsymbol{R}_T|}{M_h}\sum_{a,b,c,d}\int\frac{dx_a dx_b}{16\pi\bar{z}} \times f_1^a(x_a)h_1^b(x_b)\frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}}H_1^{\sphericalangle c}(\bar{z},M_h).$$

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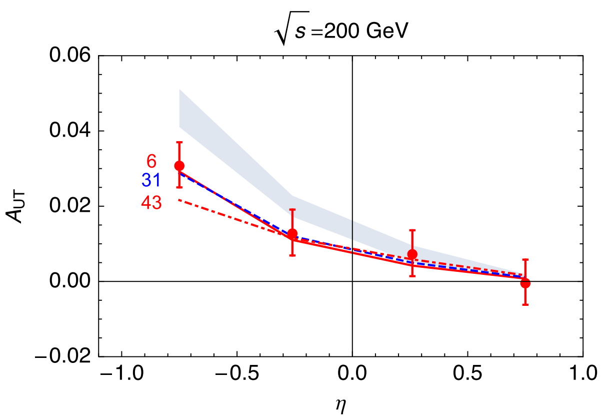

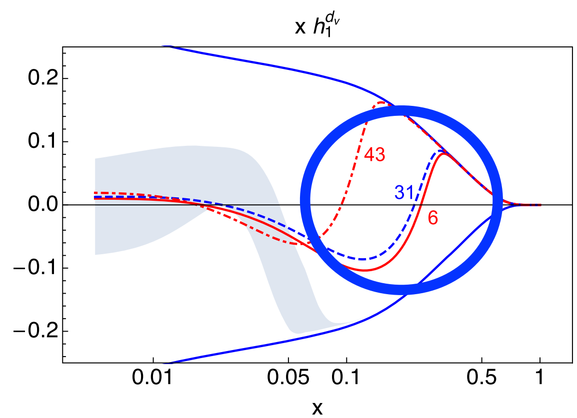

Improving errors in large-x region?
Global fit is in progress.

some replicas outside the 68% band from SIDIS fit
show compatibility with p-p data in forward kinematics

*Radici et al, P.R. D**94** (16) 034032*

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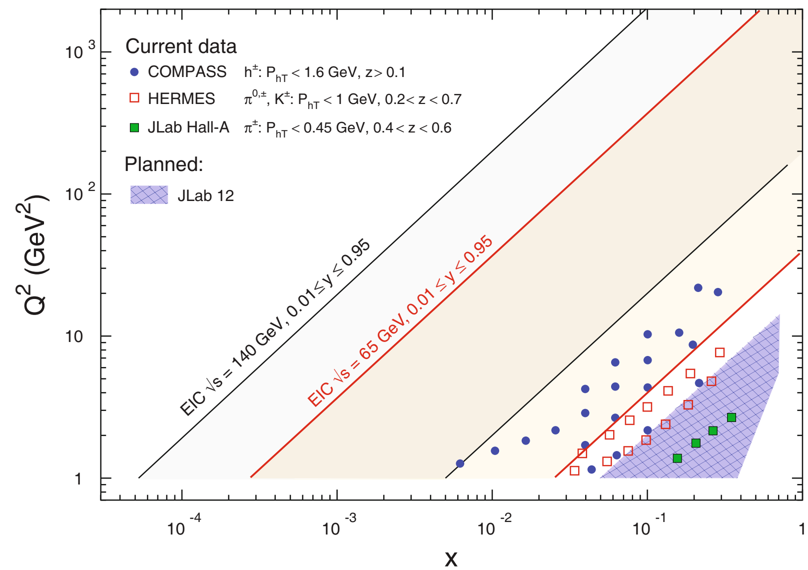
Conclusions

Discussion

- Transversity can be reliably extracted using data on single and di-hadron production. Both methods are useful to check universality of functions
- Tensor charge is useful for low energy exploration of BSM physics
- Data from JLab, RHIC, EIC will complement each other as they explore different kinematical regions
- Data from Electron Ion Collider will allow
  - Extend data to low-x region
  - Explore high-Q and high-x region to complement JLab, thus explore TMD higher twist contributions



- Possible important related topics (not covered in this talk):
  - Test relationship between collinear and TMD treatment — *See talk by Leonard Gamberg*
  - Separate reliably beam and target fragmentation regions — *See talk by Osvaldo Gonzalez*
  - Other possible ways to explore transversity using chiral-odd GPDs? — *Liuti, Goldstein, Courtoy, Gonzalez*
  - Lattice QCD studies as benchmark and/or constraints in fits? — *See talk by Rajan Gupta*
  - …